

# Avoiding stair-step artifacts in image registration for GOES-R navigation and registration assessment

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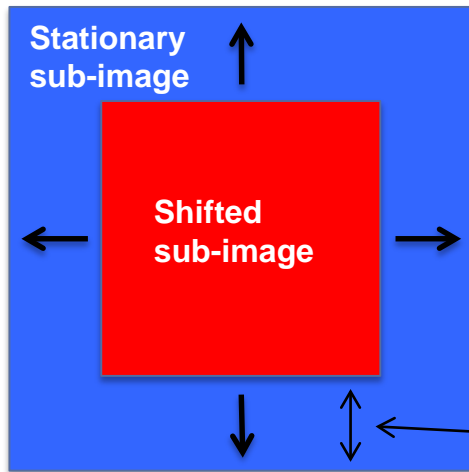
9972-30



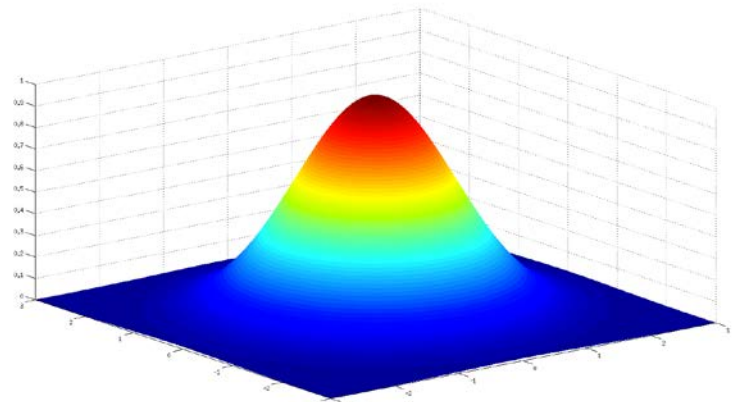
# Overview

- Stair-step is a subpixel image registration artifact
- We have seen this before... ten years ago
- GOES-R Advanced Baseline Imager (ABI) Instrument Navigation and Registration (INR) assessment
- Methods to reduce the stair-step artifact
- Conclusions

# Shift Estimation using Image Registration



Calculation of similarity metric for each EW/NS shift in image plane produces 2D array of similarity metrics in correlation plane



Location of similarity metric local maximum relative to unshifted location measures registration error

- **Similarity metric uses a form of image correlation**
  - *Normalized cross-correlation (Pearson coefficient)*
  - *Normalized Mutual Information (NMI)*
  - *Phase Correlator (Fourier processing)*
- **Output increases as images are shifted towards perfect alignment**
  - *Inputs are pixelated with same pixel size*
  - *Output is similarly pixelated*
  - *Maximum location shows image shift to nearest pixel*
- **Interpolation is required to estimate sub-pixel registration**
  - *Stair-step is an interpolation artifact*

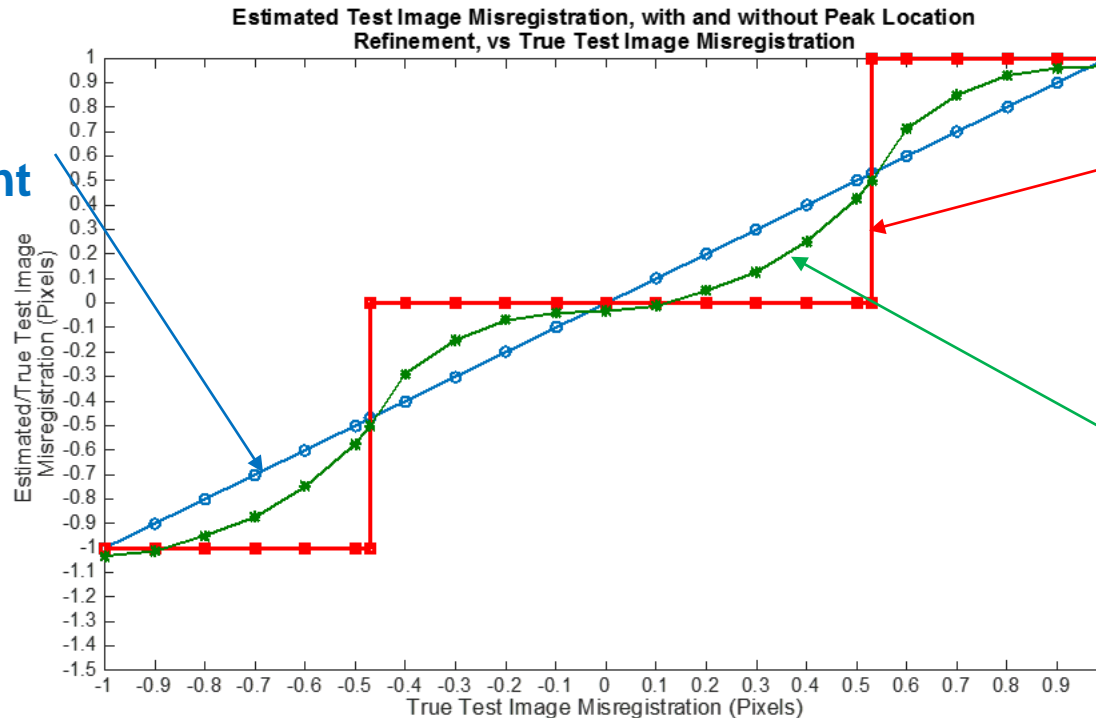
Illustrations from De Luccia et.al., Proc. SPIE 988119

**Common concept for measuring GOES-R INR metrics**

# Characteristics of the Stair-Step Artifact

Subtitle

True  
Displacement



Initial Estimate  
(Nearest Pixel)

Final Estimate  
with Stair-Step

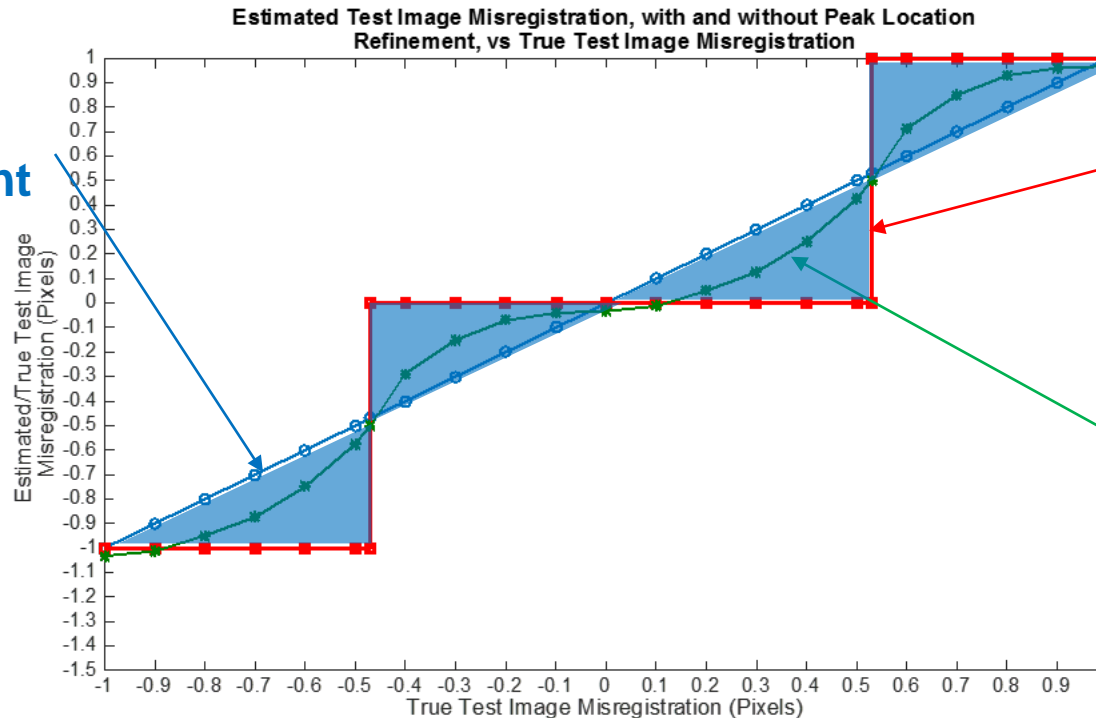
- This chart shows the position estimate for a pair of images as the true shift varies from -1 to 1 pixel
- The initial estimate of registration is the nearest-pixel location
- We fit the correlation peak with a quadratic for the final estimate
  - *Correct for offsets of an integer number of pixels*

***Stair-step is a sub-pixel estimation artifact***

# Characteristics of the Stair-Step Artifact

Subtitle

True  
Displacement



Initial Estimate  
(Nearest Pixel)

Final Estimate  
with Stair-Step

- We fit the correlation peak with a quadratic for the final estimate
  - *Correct for offsets of an integer number of pixels*
  - *Subpixel shifts require interpolation which can introduce stair-step*
    - Estimates with stair-step fall between the true location and the nearest neighbor in the blue zone

***Stair-step is a sub-pixel estimation artifact***



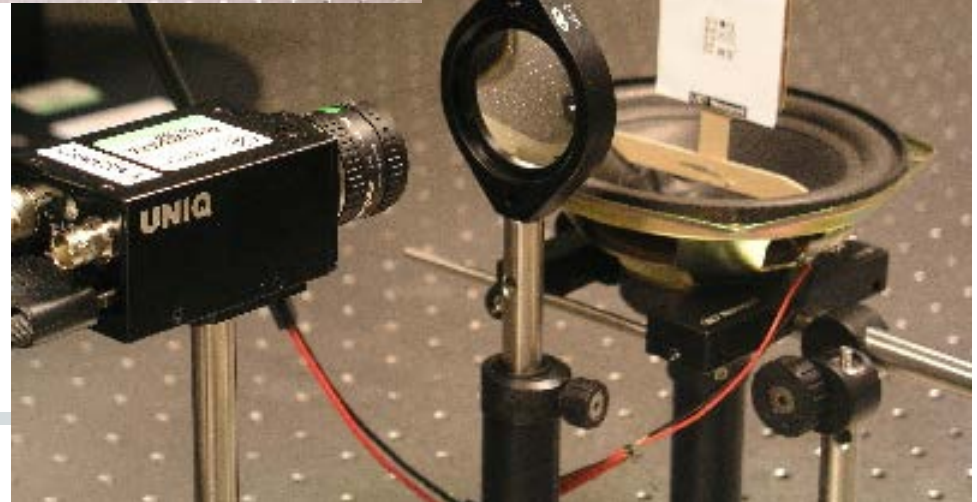
# Ten Years Ago....



Third Generation (all optical) Correlator

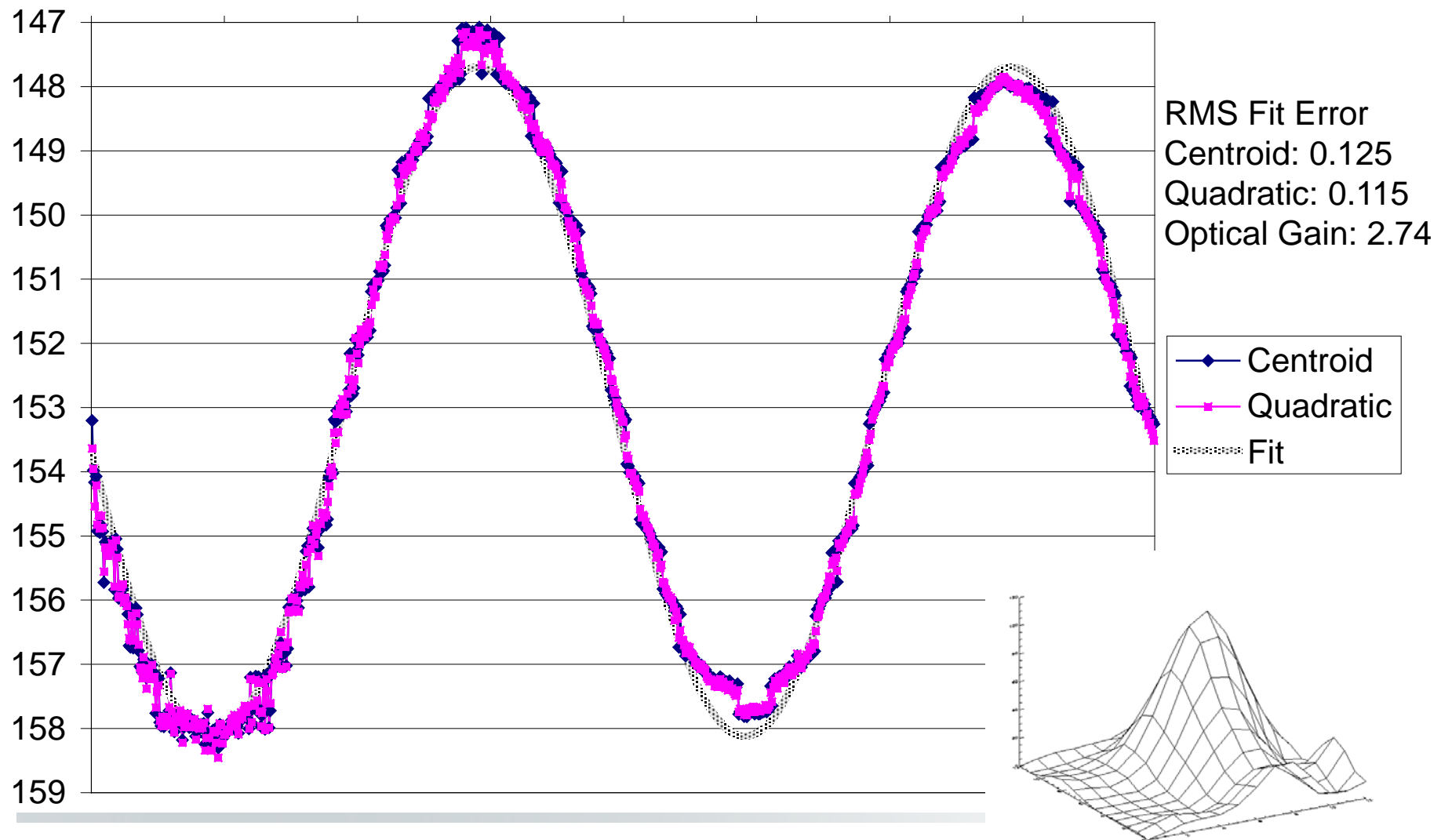
*Spring 2006*

Operated in burst mode (5-150 frames)  
Input camera operates at 400 FPS  
Input pre-processing at 50 FPS  
Optical correlator operates at 50 FPS  
(Hamamatsu OASLM has ~12 ms response time)  
Correlation location calculated 50 FPS  
Output interpretation takes minutes



Material from Grycewicz et.al., Proc. SPIE 66950J

# All-Optical Correlator Registration Results



Material from Grycewicz et.al., Proc. SPIE 66950J

e-mail address  
Department/subdivision name

# Stair-Step is Hard to Detect

## *A sub-pixel artifact*

- Stair-step is a sub-pixel artifact
  - *It won't be seen except in an experiment with sub-pixel image displacement and sub-pixel ground truth*
  - *Typically small—on order tenth pixel*
- Registration is typically a point estimate
  - *You don't typically have a line of motion to estimate*
  - *One estimate—one error*
  - *Error is a combination of many system noise terms, including stair-step*
- In the ABI case, our goal is to detect and measure subpixel misregistrations
  - *If present, the effect of stair-step will be to make the ABI images appear better registered than they actually are*

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***Stair-step is easy to miss, and easy to ignore***



# GOES-R INR Assessment

- In March 2014 the GOES-R flight project initiated two efforts to develop tools for independent evaluation of on-orbit Image Navigation and Registration (INR) performance
  - *The Product Monitor (PM), developed by the ground project, provides heritage capability for INR performance assessment*
  - *An independently developed capability for INR performance assessment using different techniques for risk reduction*
- INR Performance Assessment Tool Set (IPATS) has been developed to:
  - *Independently measure INR performance characteristics*
  - *Generate image-level and multi-image-level statistics*
  - *Provide data visualization capability*
  - *Archive results*
- Aerospace is the primary architect and developer of IPATS, with final development and test ongoing jointly with SSAI and GST

Material from De Luccia et.al., Proc. SPIE 988119

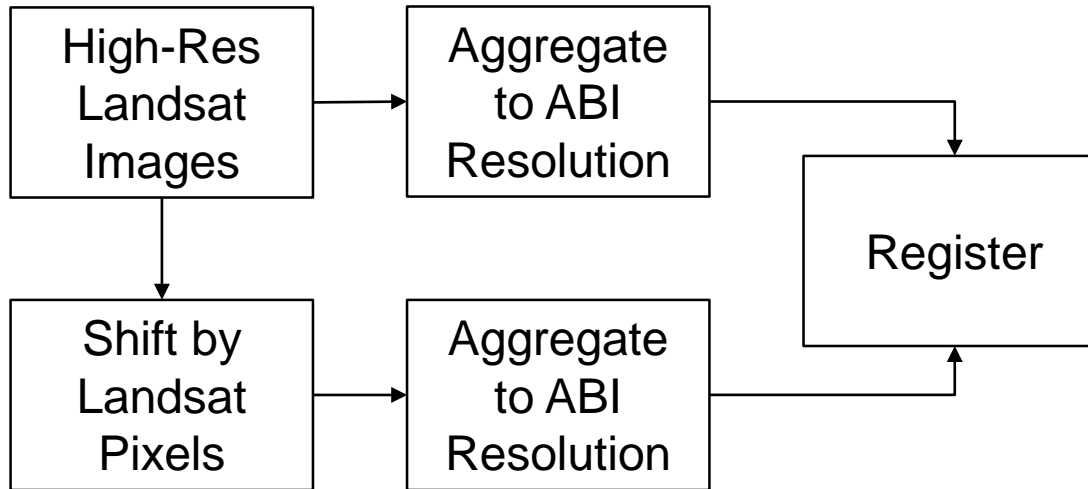
# INR metrics of interest

- Navigation (NAV) error
  - *Difference between location of pixel in data product and true location*
- Frame-to-frame registration (FFR) error
  - *Relative navigation error of corresponding pixels of same band in consecutive images*
- Within-frame registration (WIFR) error
  - *Difference between radial separation of two pixels on the FG and their true angular separation*
- Swath-to-swath registration (SSR) error
  - *Relative navigation error of two neighboring pixels on opposite sides of image swath boundary*
- Channel-to-channel registration (CCR) error
  - *Relative navigation error of corresponding pixels of different bands in the same frame*

Material from De Luccia et.al., Proc. SPIE 988119

**Key metric for any type of error is “3-sigma error”, 99.73<sup>rd</sup> percentile of distribution of error magnitudes over a 24 hour data collection period.**

# Simulation Methodology

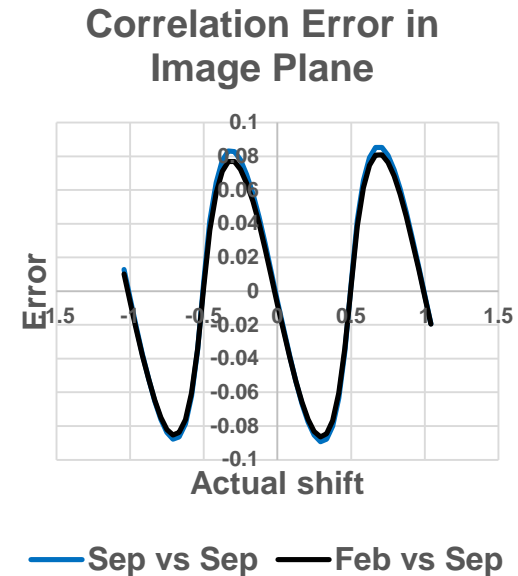
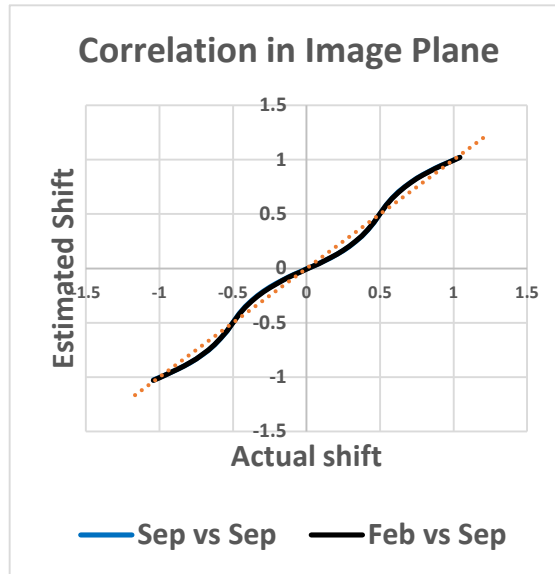
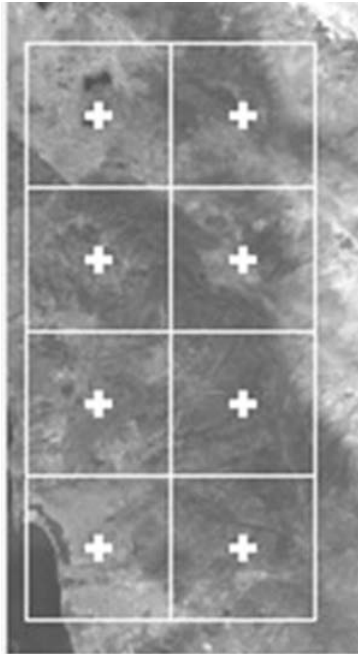


- Use IPATS tools and processes to register surrogate images
  - *Surrogate images have known ground truth*
- Landsat images aggregated 25x25 or 33x33
  - *Registered images have GOES-like GSD of 750-1000 m*
  - *Subpixel shifts in 0.03 or 0.04 pixel increments*
- Used to simulate in-channel and channel-to-channel registration

**Register images with known relative shift**

# Stair-Step in Surrogate GOES-R Images

*Simulations built with Landsat data*



- Simulations use set of eight Landsat 64x64 pixel band 3 (red) chips
- Normalized cross-correlation (Pearson coefficient)
- Simulated motion by individual Landsat pixels (1/25 GOES pixel)
- RMS error 0.06 pixels

***Stair-step seen in early simulations***

# Stair-Step Artifact in Simulated GOES-R Images

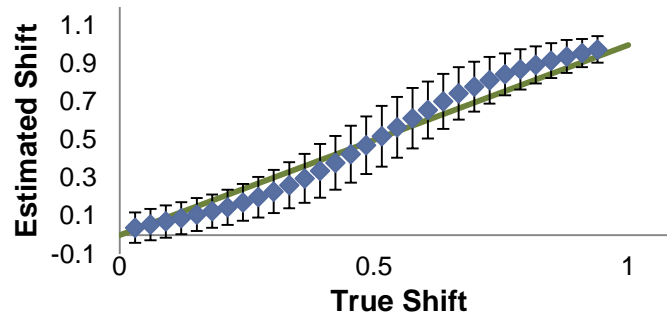
- 30x30 pixel chip simulated from Landsat 7 band 3 (red)



## Cross Correlation

Max  $3 \times \text{STD} = 0.160$

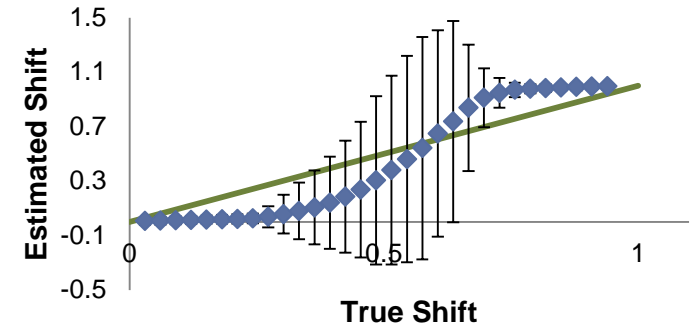
Min  $3 \times \text{STD} = 0.070$



## CC + Sobel

Max  $3 \times \text{STD} = 0.816$

Min  $3 \times \text{STD} = 0.023$

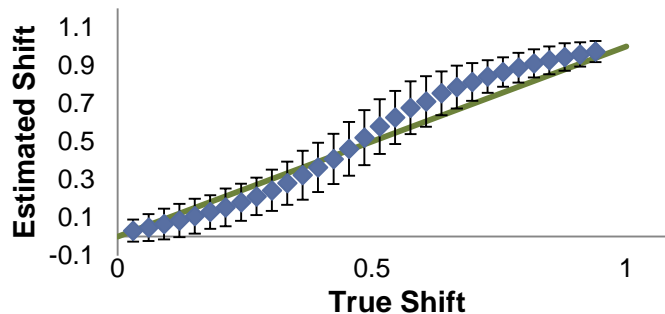


- Set of 961 images
- Shifted by multiples of  $1/33$  pixel

## Normalized Mutual Information

Max  $3 \times \text{STD} = 0.144$

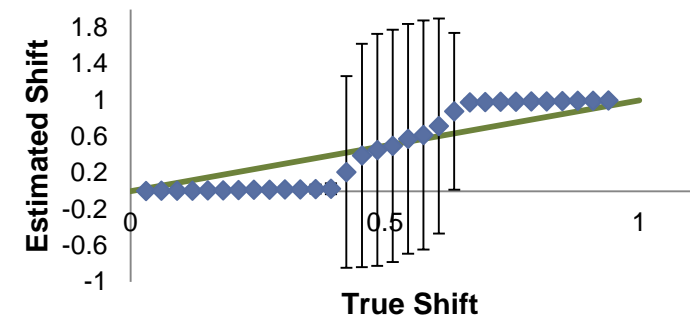
Min  $3 \times \text{STD} = 0.055$



## NMI + Sobel

Max  $3 \times \text{STD} = 1.279$

Min  $3 \times \text{STD} = 0.017$

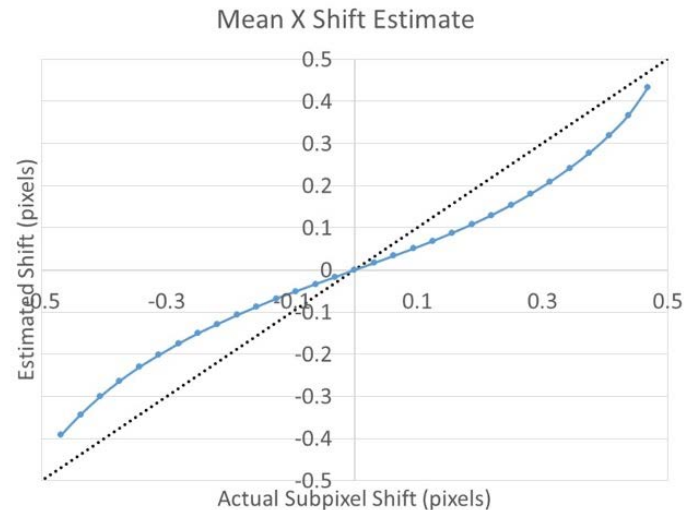


**Stair-step is seen with many correlator types**



# Image Set Run in IPATS

*Simulation set used to characterize correlation techniques*



- This Landsat image of Haiti was used for simulations both within and outside of the IPATS framework
- The boxes define 30 pixel x 30 pixel ABI correlation regions
- Visible and infrared bands were correlated

# How can we reduce the size of the stair-step artifact?

- Increase the resolution
  - *By estimating with high-resolution inputs, we get a high-resolution output*
  - *Need to start with high-resolution inputs, otherwise its just interpolation*
- Estimate the error and subtract
  - *If we can estimate the error, we can compensate*
  - *A sinusoidal estimate works well for mild stair-step*
- Choose a different correlator
  - *Different correlators have different stair-step response*
- Choose a different output interpolator
  - *Stair-step is an interpolation artifact*
  - *Choosing a good interpolator is critical*

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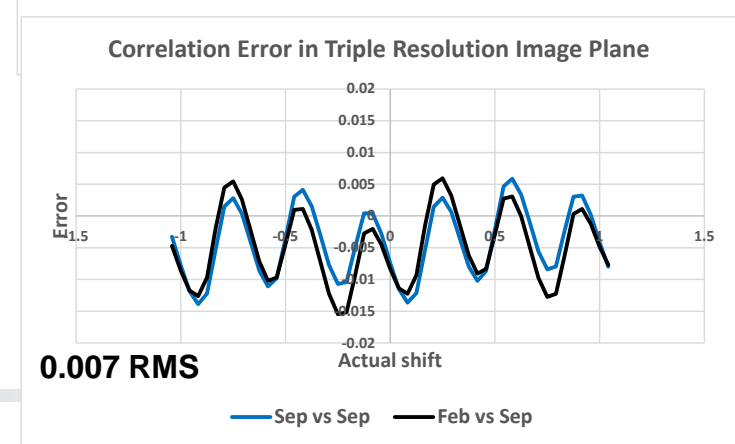
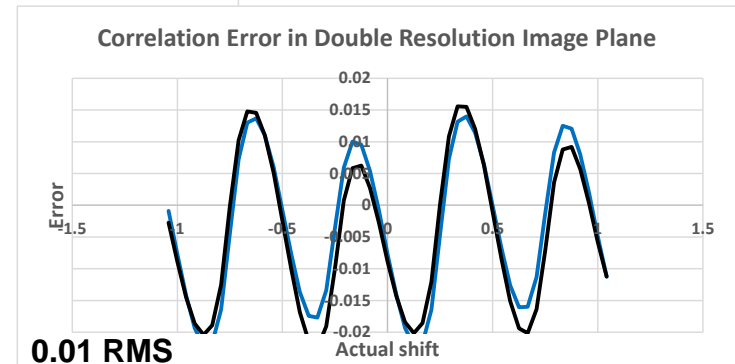
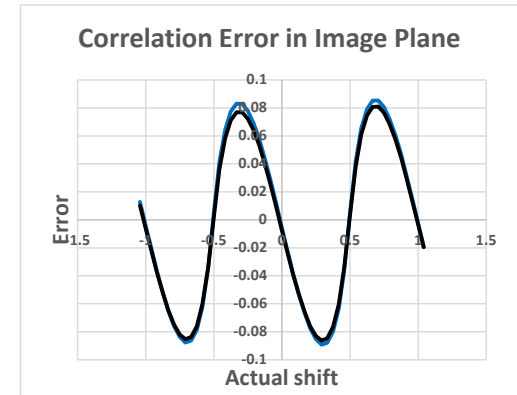
***We are in the middle of a performance trade***

# Increase Reference Resolution

*Data from surrogate ABI images on slide 12*

- Increasing the reference resolution results in a large reduction in the magnitude of stair-step
- Correlation done at the smaller pixel size
  - *The spatial period of the stair-step is reduced to the smaller pixel size*
- This works well for NAV assessment
  - *Reference chips can have arbitrary scale*
- Requires that one of inputs is available at high-resolution
  - *Not helpful for CCR or FFR*
  - *When both images are rescaled, interpolating the inputs is similar to interpolating the output, but has computational disadvantages*

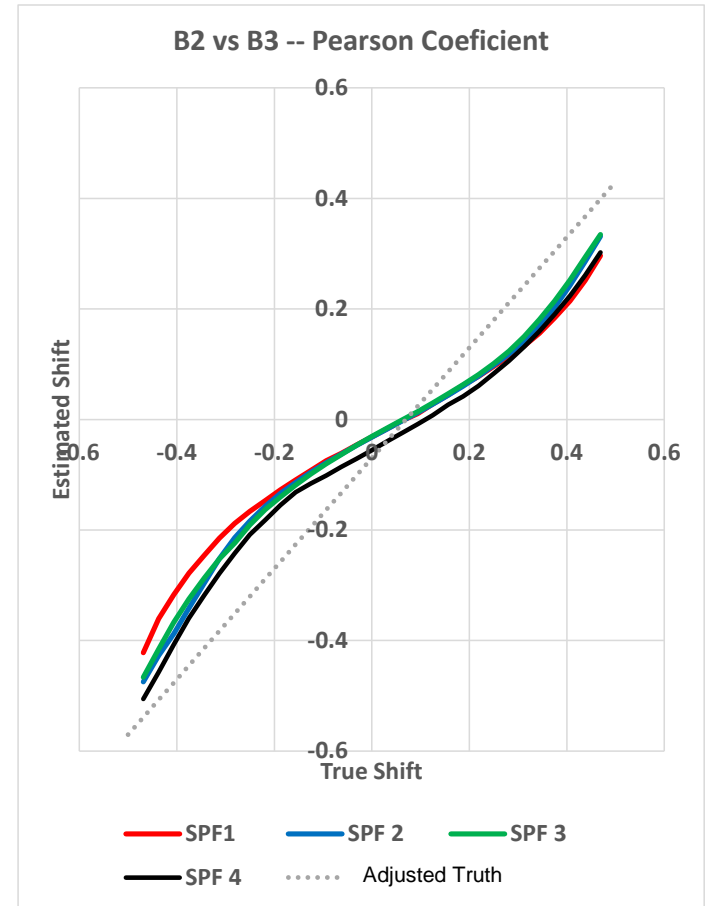
**Good NAV technique**



# Increasing Resolution by Interpolation of Both Inputs

*Data from surrogate ABI images on slide 14*

- Linear interpolation results in similar registration metrics at all zoom factors
  - Here, *SPF* = *Sub-Pixel Factor* = amount of linear interpolation
- These correlations were all done within IPATS
- Very little difference is seen in the results
- “Truth” line has been adjusted for observed channel-to channel offset

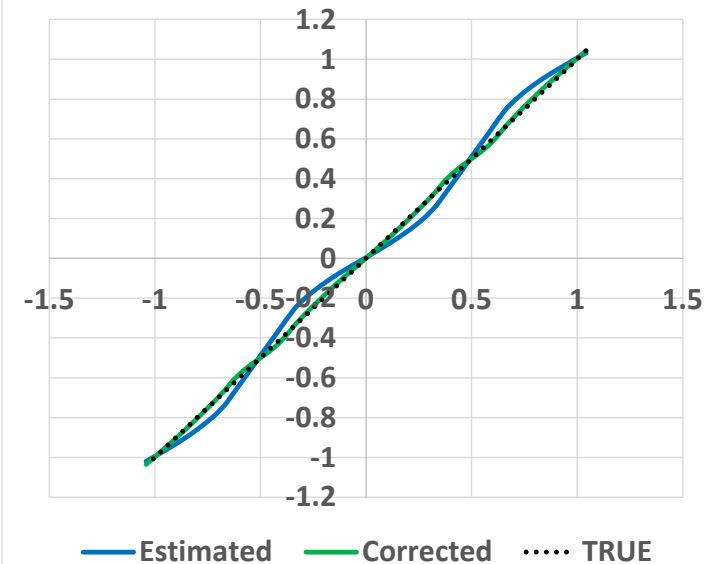


# Estimate the Error and Subtract

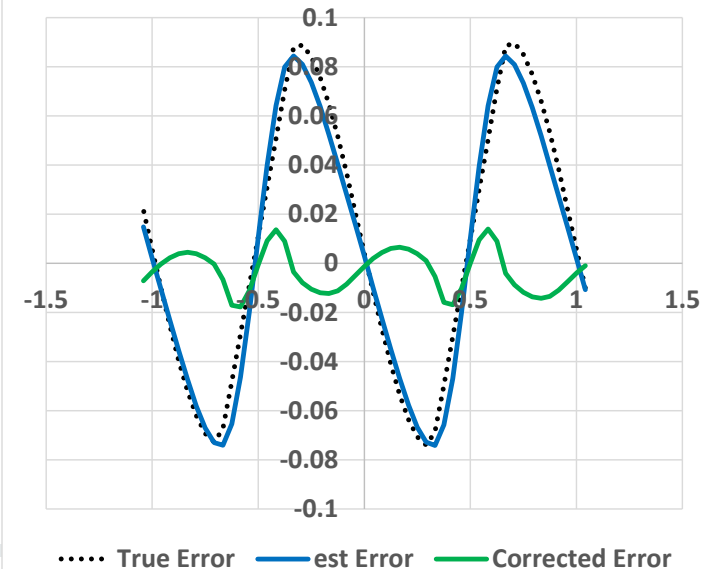
*Data from surrogate ABI images on slide 12*

- A small stair-case is estimated by a sinusoidal offset
  - Zeroes at whole and half pixel shifts
  - Maxima at  $\frac{1}{4}$  and  $\frac{3}{4}$  pixel shifts
  - Magnitude can be estimated by modeling
- Stair-case cannot be eliminated this way, but can be greatly reduced

Original and Corrected Estimate



Error Estimate



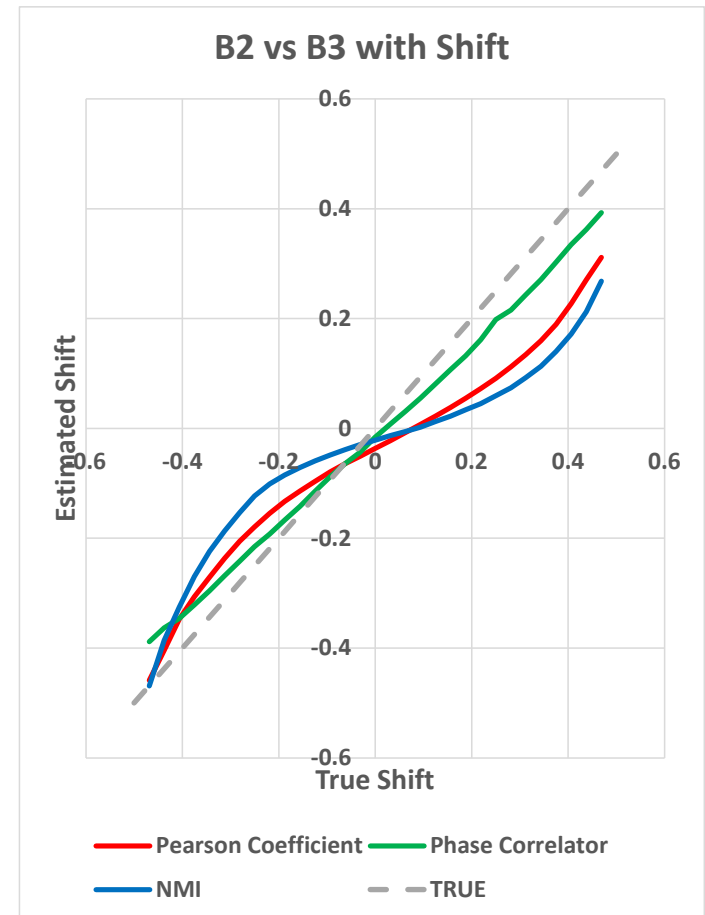
**Method-of-choice for FFR, SSR, and CCR**



# Choose a Better Correlator

*Data from surrogate ABI images on slide 12*

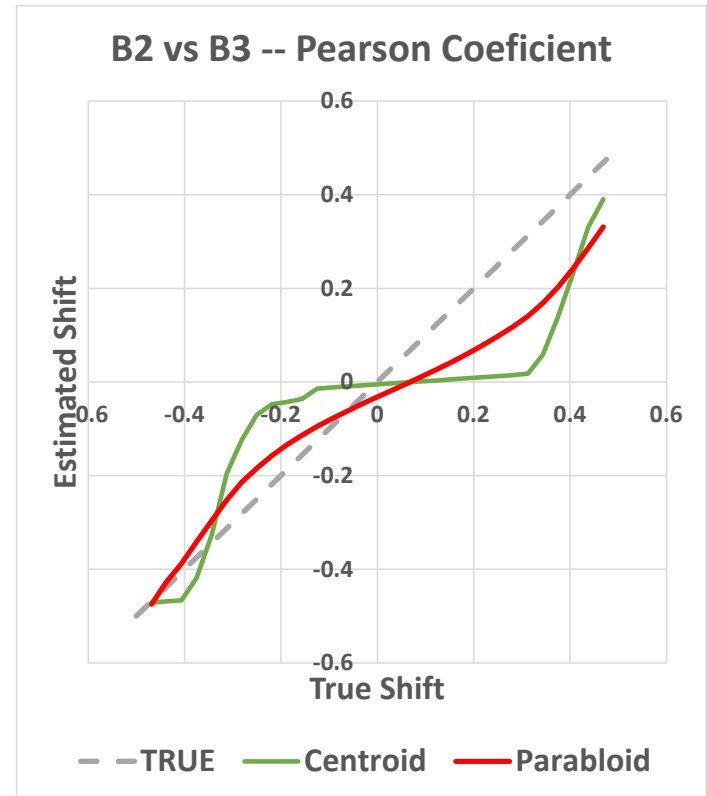
- Normalized Cross-Correlation (NCC) performs better than NMI when images are in similar bands
  - *NMI has an advantage for dissimilar CCR combinations—visible to IR*
- A phase-space correlator operating in the Fourier domain is being evaluated as an alternate solution



# Choose a Better Output Interpolator

*Data from surrogate ABI images on slide 12*

- The goal is to find the location of the primary peak in the output correlation plane at subpixel accuracy
- We have evaluated two interpolators
  - *Both interpolators start at the location defined by the largest value in the correlation plane*
  - *The “Centroid” interpolator finds the center-of-mass of the pixels in a 5x5 region about the peak in the correlation plane*
  - *The “Parabolic” interpolator fits one-dimensional parabolas to the correlation peak in the x and y dimensions*



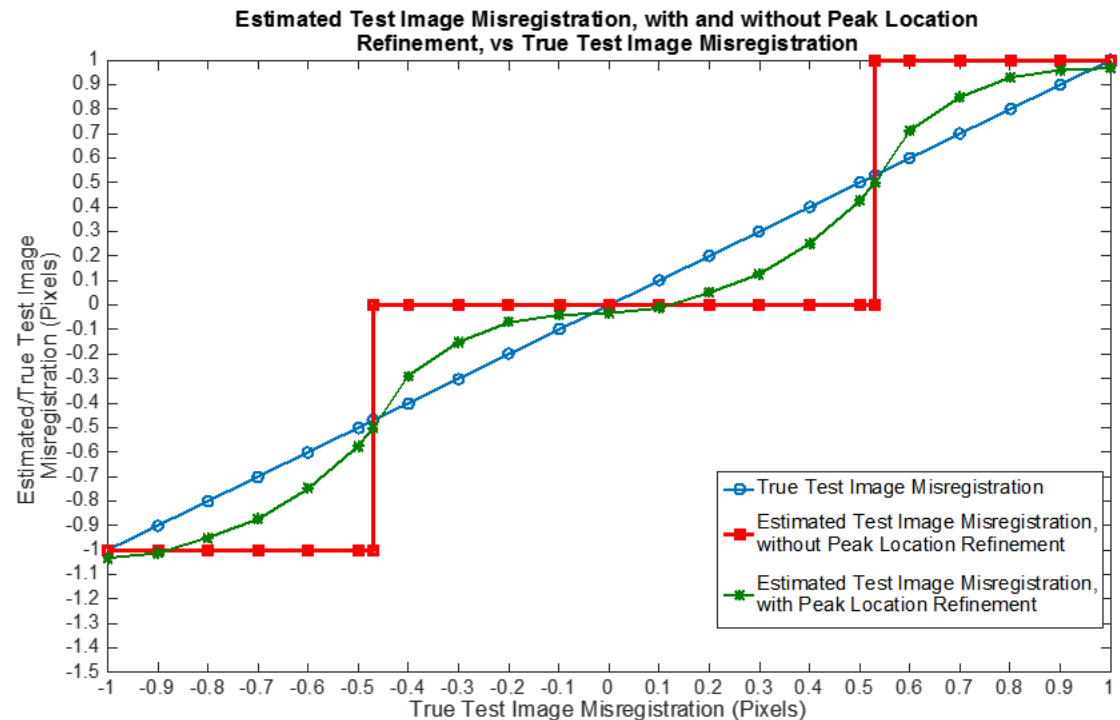
# Conclusions

- We have described the stair-step registration artifact
- We have shown this may be an issue for GOES-R ABI registration
  - *Of order tenth pixel if misregistration is spread across a full pixel*
  - *Much smaller if misregistration is always a quarter pixel or less*
  - *Estimated subpixel misregistration smaller than actual*
- Effect of stair-step can be minimized
  - *Good choice of correlator*
  - *Good choice of interpolator*
  - *Remaining effect can be estimated and compensated*

# Backup

# But Why?

## A Notional Explanation

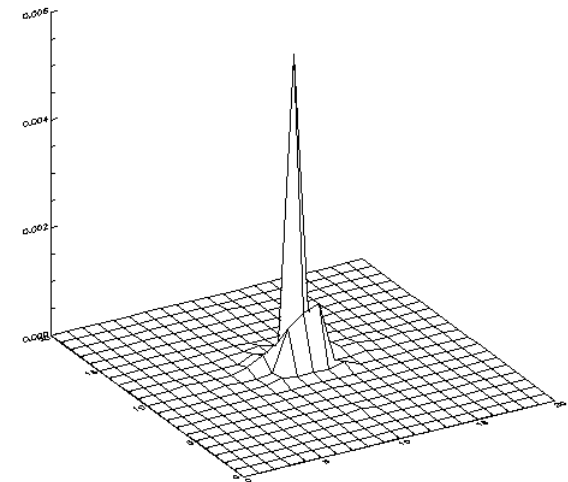
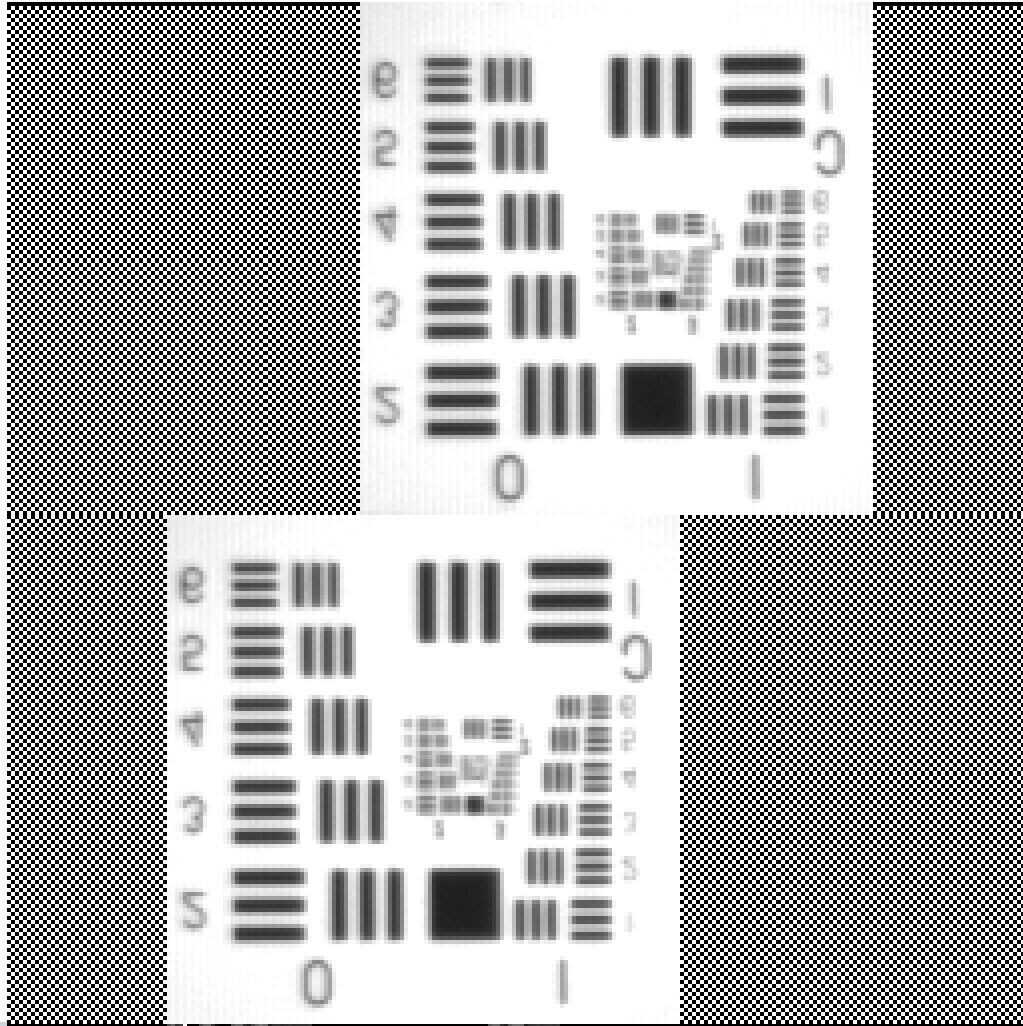


- I plan to build an animation here showing how the stair-step must arise if you start with an assumption that the measured values are correct in a region around the sample point
  - *That is, you get stair-step if you estimate the points but don't estimate or under-estimate the slopes*
  - *Frank—I believe that the parabolic refinement will estimate the line with minimum slope that passes through three points. Is this true?*

**We assume an area around the measurement to be correct**

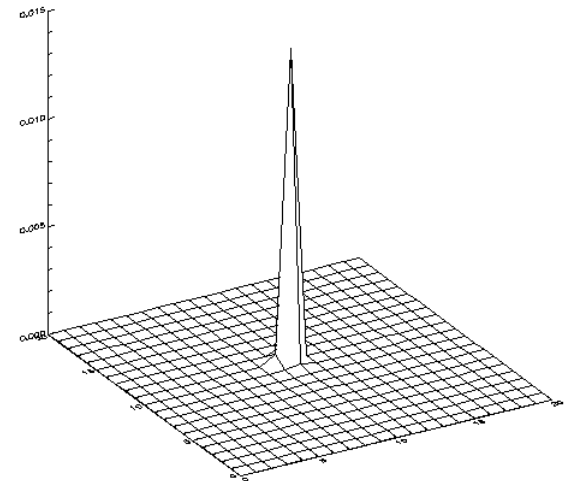
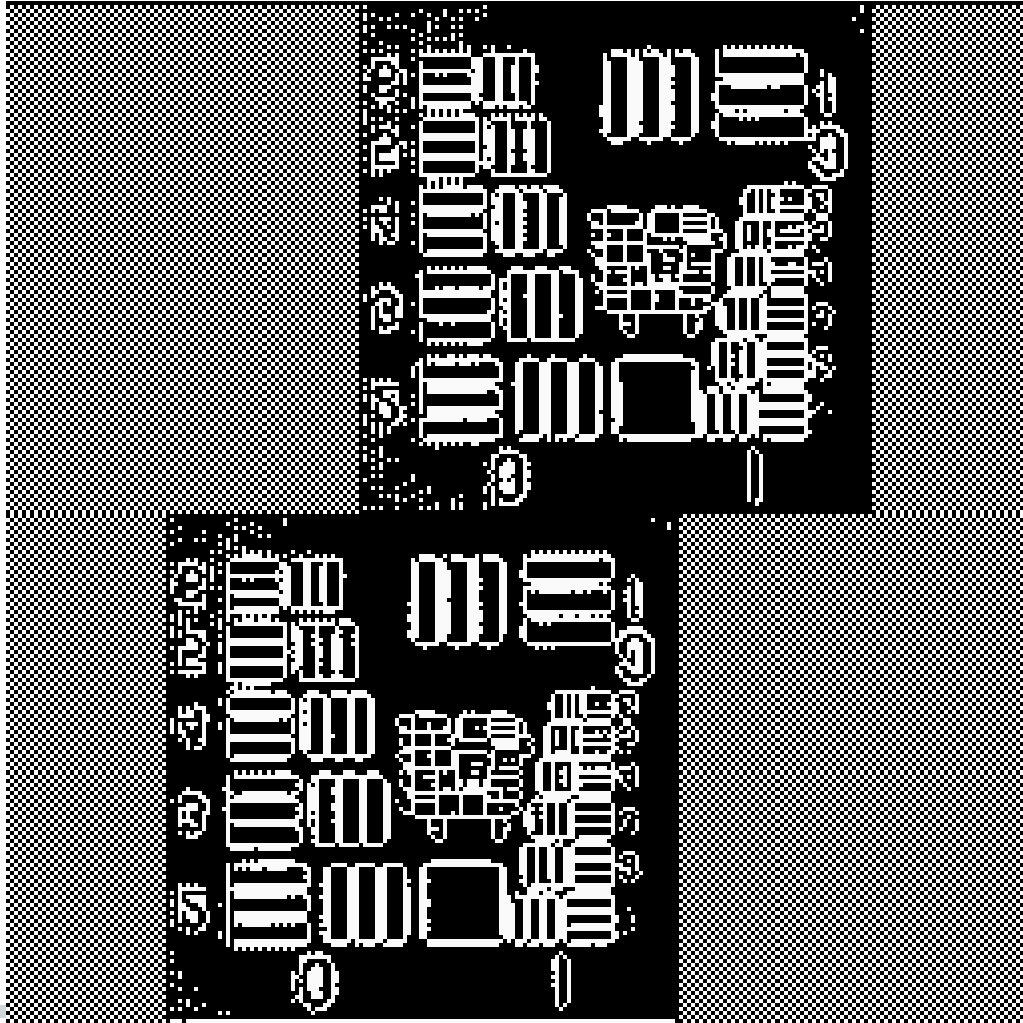


# Linear JTC Input and Correlation Peak



- Correlation computed digitally

# Binary JTC Input and Correlation Peak

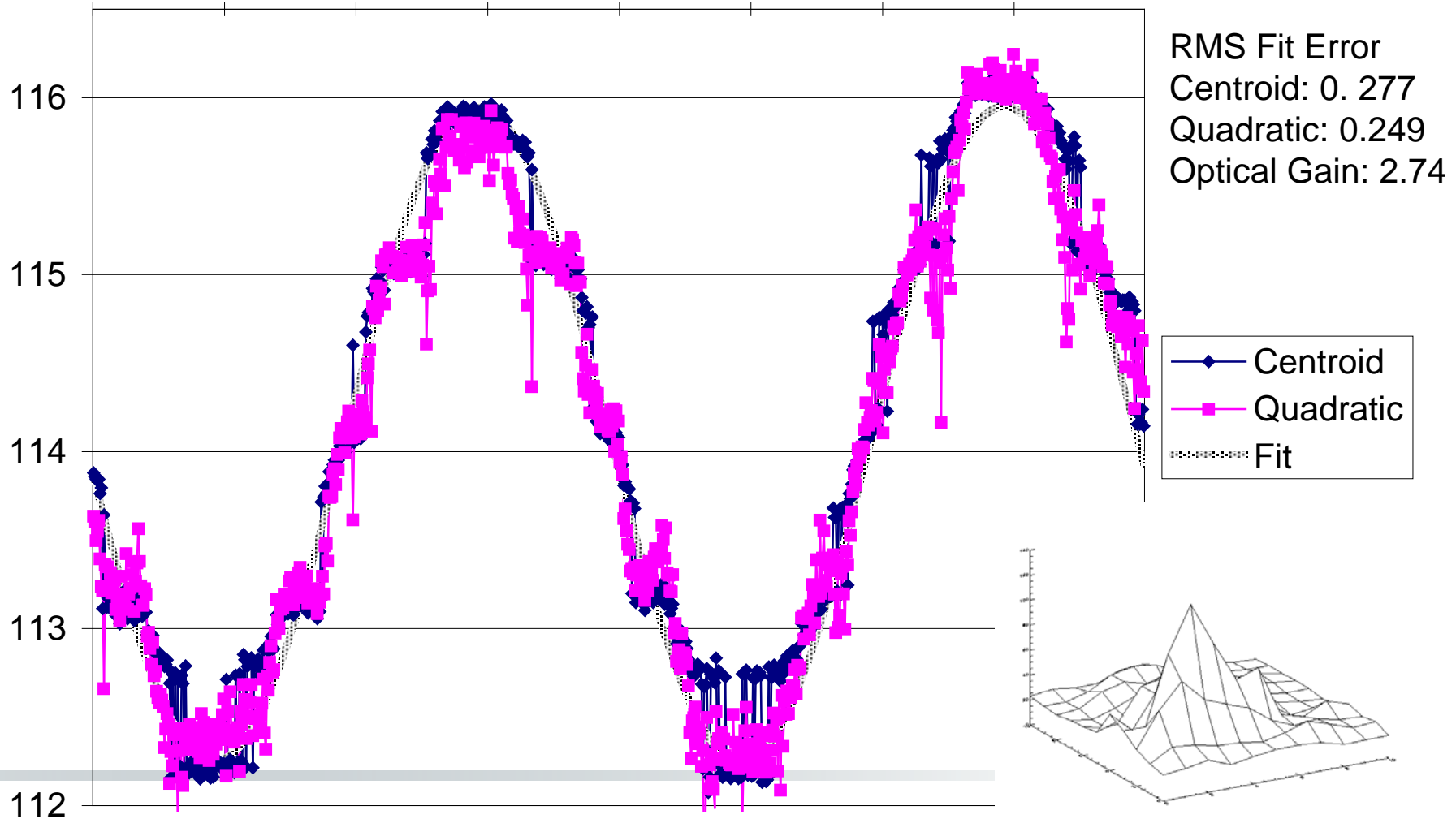


- Binarized by convolving with Laplacian kernel and thresholding
- Correlation computed digitally

Material from Grycewicz et.al., Proc. SPIE 66950J

# Two-Stage Joint Transform Correlator, Binary Input

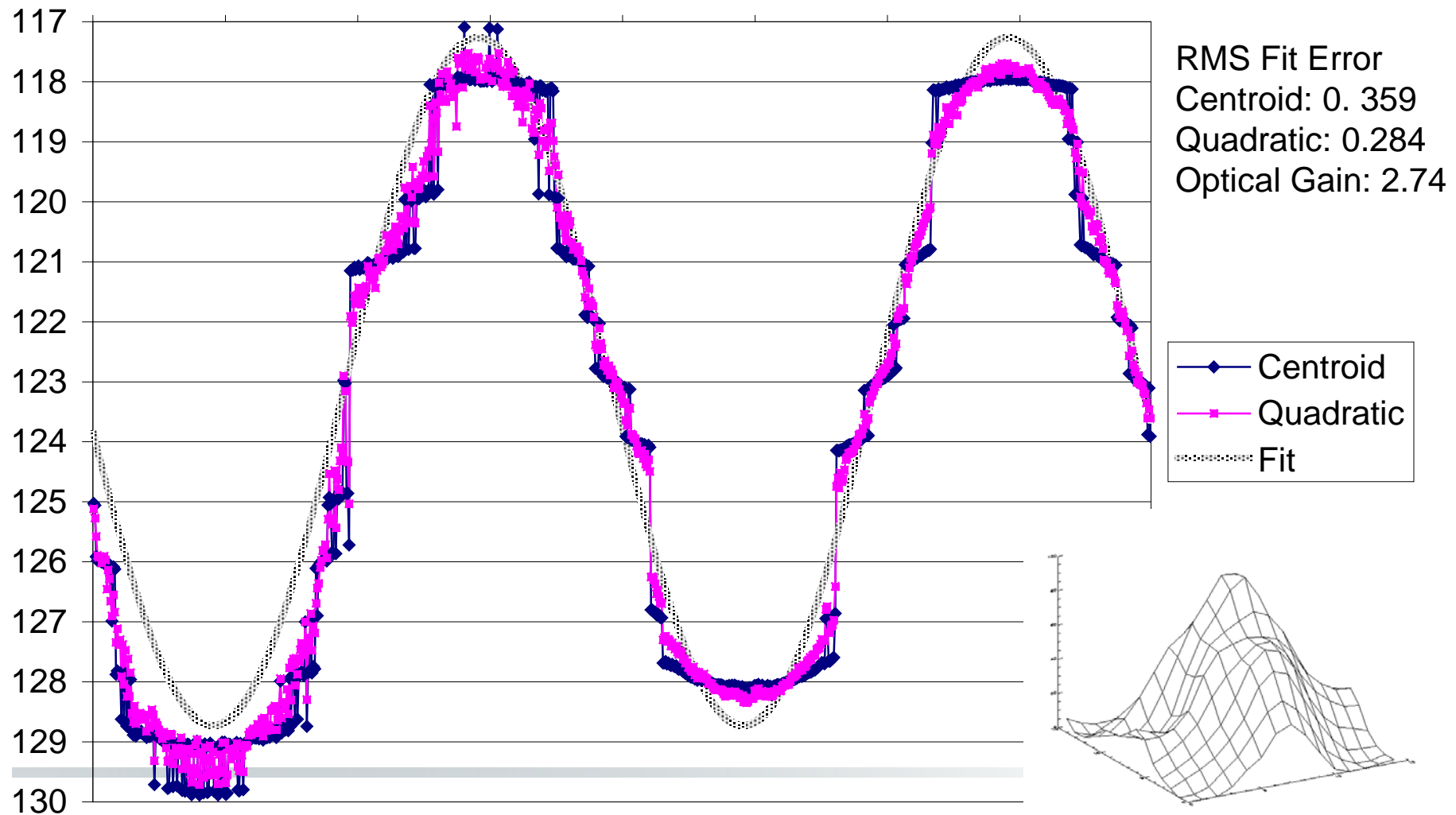
## Two Stage BJTC



112  
Material from Grycewicz et.al., Proc. SPIE 66950J

# All-Optical JTC, Linear Input

## OASLM - Linear Input



Material from Grycewicz et.al., Proc. SPIE 66950J